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Diamond Dome Oxidation Flight Boundaries

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FOREWORD

Diamond domes are under development for high speed missiles. This final report describes a study to determine the missile flight conditions where oxidation of a hot diamond dome could limit performance. The time for a diamond dome to reach 800-1000°C was calculated for various speeds and altitudes, and these times were compared with the time required for degradation of the infrared transmission of diamond windows when heated in air at 800-900°C. The experimental work was carried out from August through October 1994.

The work was performed in the Aeromechanics and Thermal Analysis Section of the Airframe Branch of the Airframe, Ordnance, and Propulsion Division, and in the Materials Synthesis Section of the Chemistry and Materials Branch of the Research and Technology Division. The project was sponsored by the Office of Naval Research (Contract N0001494WX23016) and has been reviewed for technical accuracy by Daniel C. Harris and Gene A. Jaeger.

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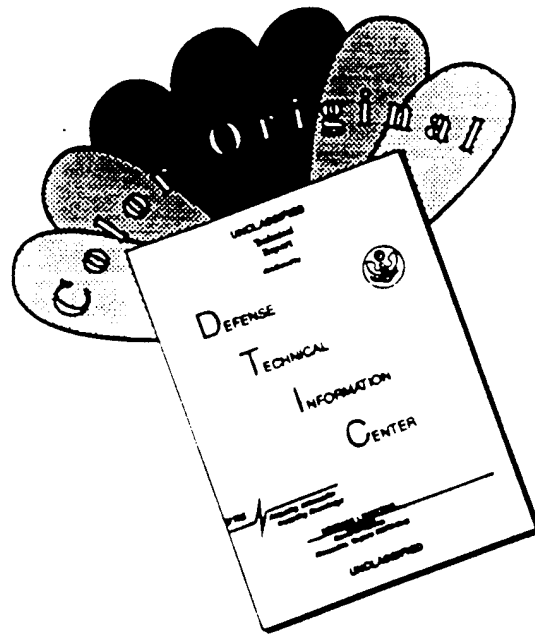
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13. ABSTRACT (Maximum 200 words)

(U) A parametric study was conducted on the aerodynamic heating of a hypothetical hemispherical diamond dome. Flight was assumed to occur at constant altitude and Mach number. The times required for the maximum temperature on the dome to reach 800, 900, and 1000°C were calculated, covering the temperature range where diamond oxidation becomes rapid. The parametric matrix included altitudes from zero to 200,000 ft, and Mach numbers from 3.9 or 4.1 to 8.0. For Mach 5 at sea level, the dome would reach 800°C in 4.5 s, 900°C in 6.5 s, and 1000°C in 9 s, while the total (or stagnation) temperature would be about 1250°C. Significant temperature variations throughout the dome were calculated, especially as a function of angular position around the dome. For example, at Mach 5.5 and 20,000 ft the stagnation point of the dome reached 900°C in 9 s, while the edge of the dome 90° away was 200°C cooler. Oxidation would not be a concern for flights up to about Mach 4, while at Mach 5 and above flights would be limited to short durations or high altitudes. Diamond dome temperatures can also be calculated for specific flight profiles, and examples are provided for sample medium and long range anti-air missiles. These studies show that time of flight, speed, and altitude are all key parameters that would affect the oxidation of diamond domes. The information provided is valuable for assessing oxidation-limited flight conditions for diamond domes.

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INTRODUCTION

Polycrystalline diamond prepared by chemical vapor deposition (CVD) is under development as a missile dome material (Reference 1). Diamond has exceptional properties important for a high speed missile dome including high thermal shock resistance and excellent optical transparency (except in the mid-wave infrared (IR) region). Aside from issues of fabrication and optimization of extrinsic properties, one of the operational limits of diamond domes relates to oxidation of diamond that occurs at elevated temperatures in the presence of oxygen. Air oxidation of diamond has an onset at 480°C (Reference 2) and proceeds at significant rates above 600°C (References 3 and 4). However, the initial rate of diamond oxidation is typically much slower than the rate at later times, apparently due to initial low microscopic surface area compared to the rough surface of partially oxidized samples (References 4 and 5). A recent study at the Naval Air Warfare Center Weapons Division (NAWCWPNS) determined the effects of heating diamond in air for short times (45-555 seconds (s)) at 700-900°C (Reference 5). Significant degradation of IR transmission occurred for CVD diamond when heated in a furnace at 800°C for 75 s in air. The drop in IR transmission was due to scatter caused by roughening of the surface and selective etching at grain boundaries. In contrast, natural type IIa diamond (single crystal, no grain boundaries) showed little change when heated at 800°C for 255 s and only a slight loss in IR transmission after heating at 900°C for 45 s.

The oxidation study showed that time and temperature are critical parameters in defining the oxidation resistance of diamond. A diamond missile dome in flight would undergo aerodynamic heating with the temperature dependent upon the particular flight profile. This study was conducted to determine the times required for diamond domes to reach temperatures where diamond oxidation is rapid ($\geq 800^\circ\text{C}$), in order to aid in the assessment of oxidation-limited flight conditions for diamond domes.

BACKGROUND

Parameters important in the aerodynamic heating of a diamond missile dome include speed, altitude, and time. Based on the oxidation/IR transmission study mentioned above (Reference 5), three temperatures (800, 900, and 1000°C) were chosen in the range where diamond dome oxidation would be rapid. The times required for the maximum dome temperature to reach these three temperatures were determined at various constant free-stream Mach and altitude conditions. This parametric study will assist in determining the operability of diamond domes for extended free flight at high speeds.

ANALYSIS OF DIAMOND DOME TEMPERATURES

ANALYSIS PROCEDURES

An axisymmetric finite element model of the 1.5 inch (3.81 centimeters (cm)) radius hemispherical diamond dome was created using the PATRAN program (Reference 6). Thirty-six nodes were spaced around the dome's surface, and eleven nodes were spaced through the 2.54 millimeter (mm) thickness with nodes clustered near the outer surface (Figure 1). To calculate transient dome temperatures, a Systems Improved Numerical Deficiency Analyzer (SINDA) heat transfer network model (Reference 7) was generated from the finite element model, and the initial model node temperatures were set to 27°C for all cases. Given the wide temperature range during the transient heating, temperature-dependent CVD diamond properties (References 8 and 9) were used in the SINDA model. On the exterior surface of the dome, an aerodynamic heating boundary condition was applied, but radiation was neglected, and all other dome boundaries were adiabatic.

Aerodynamic heating of the diamond dome was calculated using results from the Advanced Ballistic Re-entry System Shape Change Code (ASCC) program, a code that uses engineering methods to compute supersonic/hypersonic aerodynamic heating of axisymmetric bodies (Reference 10). Cold wall (27°C) heat transfer coefficients and recovery enthalpies were computed by ASCC using the 1962 U.S. standard atmosphere, and tables of this information were input to SINDA to calculate aerodynamic heating. Since the heat transfer coefficient generally decreases with increasing wall temperature, using the cold wall heat transfer coefficient regardless of the dome temperature gives higher aerodynamic heat transfer rates and, hence, shorter (conservative) times for the diamond dome to reach the target temperatures. Neglect of radiation from the exterior surface and conduction to the mount that would be in contact with an actual dome also has a conservative effect on the times calculated by reducing heat loss from the dome.

Flight was assumed to occur at constant altitude and Mach number. The parametric matrix included altitudes from 0 to 200,000 feet (ft) (at 10,000 ft intervals from 0 to 100,000 ft and 20,000 ft intervals from 100,000 to 200,000 ft) and the following Mach numbers: 4.1, 4.4, 4.7, 5.0, 5.5, 6.0, 6.5, 7.0, 7.5, and 8.0 (Mach 3.9 was added for the case of a 1-mm-thick dome). A flight condition was run only if its total temperature exceeded the dome target temperature (800, 900, or 1000°C). Figure 2 shows how the Mach number varies with altitude for different flow total temperatures (i.e., stagnation temperatures). The nonuniformity in the curves is mainly due to the nonuniform variation of temperature with altitude. Note that Mach 4.1 flight at sea level could reach 800°C, while Mach 4.1 flight at 20,000 ft could not. Consequently, there were fewer flight conditions to check at the higher target temperatures.

ANALYSIS RESULTS

Figures 3 and 4 show the times required for the maximum temperature on the dome to reach the 800°C target temperature for 2.54-mm and 1-mm-thick diamond domes (note that the speed was extended down to Mach 3.9 for the 1-mm dome). Similarly, Figures 5 and 6 show the times required to reach the 900 and 1000°C target temperatures for the

parametric matrix of conditions. If the time to reach the target temperature exceeds 900 s, that condition is not included in the results. This eliminates high altitude conditions for which the heat transfer coefficient is low. The time to temperature is inversely proportional to the heat transfer rate. The time generally increases as the altitude increases and decreases as the Mach number increases. For example, Figure 3 shows that a 2.54 mm thick dome at Mach 5.0 would reach 800°C in 4.8 s at sea level, or 11.3 s at 20,000 ft, or 34 s at 40,000 ft. At Mach 8.0 the times to reach 800°C are 1 s at 20,000 ft, 12 s at 100,000 ft, and 100 s at 200,000 ft. At short times the maximum dome temperature can be well below the total temperature. At Mach 5 at sea level, the 2.54 mm thick dome reaches 800°C in 4.5 s, 900°C in 6.5 s, and 1000°C in 9 s, while the total temperature is about 1250°C. When the total temperature approaches the target temperature, the nonuniform variation in atmospheric temperature reflected in the curves in Figure 2 is large enough to create conditions where the time to reach the target temperature decreases as the altitude increases at a constant Mach number. This leads to odd-shaped curves such as the Mach 4.4 curve in Figure 3.

Depending on the strength of the diamond material, different thicknesses would be required. Figures 3 and 4 show that the thinner dome heats up faster due to its lower total heat capacity, with the 1-mm dome reaching 800°C in 7 s at Mach 4.1 at sea level, compared to 20 s for the 2.54-mm dome.

A considerable temperature variation can occur within the diamond dome. The extent of the temperature variation for the 900°C target temperature cases is shown in Figures 7-9 for 2.54-mm-thick domes. Figure 7 presents temperature contours for the entire dome for the case of Mach 5.5 at 20,000 ft. When the temperature at the stagnation point reaches 900°C, the temperature at the edge of the dome (90° away) is 200°C cooler. Figure 8 shows the maximum variation in temperature on the surface of a 2.54-mm-thick dome for all 900°C target temperature cases. Figure 9 details the dome external surface temperature as a function of the angle from the stagnation point for the 20,000 ft cases. Except for cases with the total temperature near the target temperature, the temperature difference around the dome decreases with increasing altitude or target temperature, and increases with increasing Mach number. The temperature variation around the dome surface is much larger than the difference through the dome thickness. For example, at Mach 8 sea level flight and 900°C target temperature, the temperature varies 575°C around the dome and 40°C through the thickness. These temperature variations are significant since diamond oxidation will not occur on the cooler portion of the dome and a seeker might function even though part of the dome is oxidized.

Analysis can also be conducted for specific flight profiles if the profile data is available. Figure 10 shows the maximum dome temperature for a diamond dome (1.5-mm thick) during various medium range anti-air missile trajectories. Two missile variants were chosen with two different flight profiles run for each missile. Figure 11 shows results of a similar calculation for a long range anti-air missile, again with two different flight profiles shown. Severe degradation in diamond dome transmission would be expected for the flight profiles in Figure 11 due to the extended time at high temperature (>1000°C for over 1 minute (min)).

The analysis results presented here along with the diamond oxidation results in Reference 5 allow for a rough quantitative assessment of the flight conditions where

diamond missile domes are likely to degrade due to oxidation. One of the remaining experimental uncertainties concerns the effect of the dynamic air flow on oxidation rate, since the experiments in Reference 5 were conducted in static air. A study on natural type IIa diamond crystals found that the oxidation rate was independent of oxygen pressure (one atmosphere oxygen pressure) at 600-700°C (Reference 4), indicating that at these temperatures the high air flow rate on a diamond dome would not affect the oxidation rate. However, a study of CVD diamond films on silicon substrates found a 0.6 reaction order in oxygen at 700-800°C (Reference 11). At some sufficiently high temperature, the oxidation of diamond will be significantly dependent on the rate of transport of fresh oxygen to the surface rather than just the high thermal activation energy (about 230 kilojoule/mole from References 3, 4, and 11) of the diamond-oxygen reaction. It is likely that at 800°C the high air flow rate on a diamond dome will not substantially increase the oxidation rate compared to the static air experiments, while at higher temperatures the effect of air flow remains an open question. Thus, diamond domes would be expected to withstand temperatures near 800°C (i.e., flight at Mach 4 to 4.5) for about a minute without significant degradation. Flights at Mach 5 and above may be restricted to shorter durations or higher altitudes to avoid oxidative degradation.

CONCLUSIONS

This parametric study considers a hemispherical diamond dome (i.e., uncovered and nose-mounted) with several assumptions about heat transfer to the dome: cold wall heat transfer coefficients are used and radiation to the environment is neglected. Also, heat conduction to the dome mount was not considered. Consequently, the times computed for the dome to reach the target temperatures are conservative and produce the most restrictive oxidation-limited flight envelope. Design techniques that reduce dome heating (such as a dome cover, a flat window, or active cooling) may be used to expand the flight envelope. In addition, the mitigating effect of the temperature variation around the dome depends on seeker design and missile operation characteristics that are not considered. However, for a first look at transient dome heating, this study provides valuable information necessary to assess oxidation-limited flight conditions for diamond domes.

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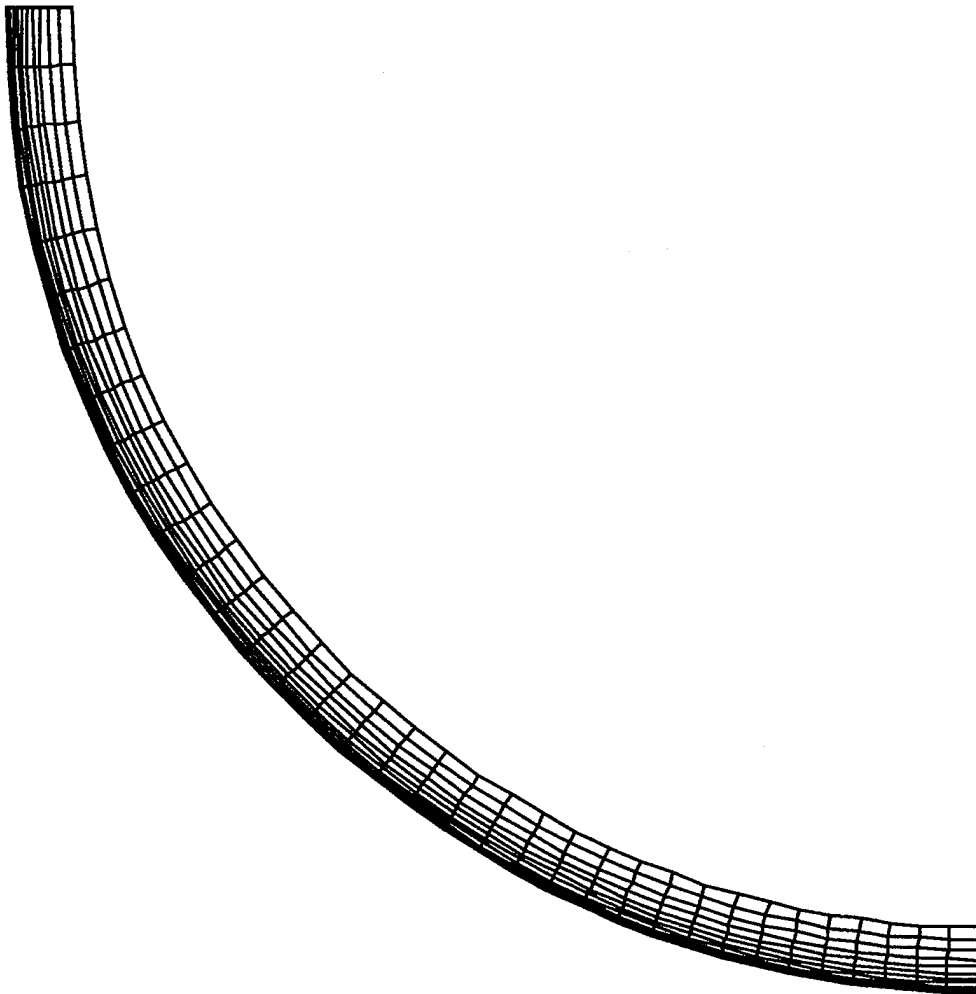


FIGURE 1. Cross-Sectional View of Diamond Dome Showing Finite Element Mesh.

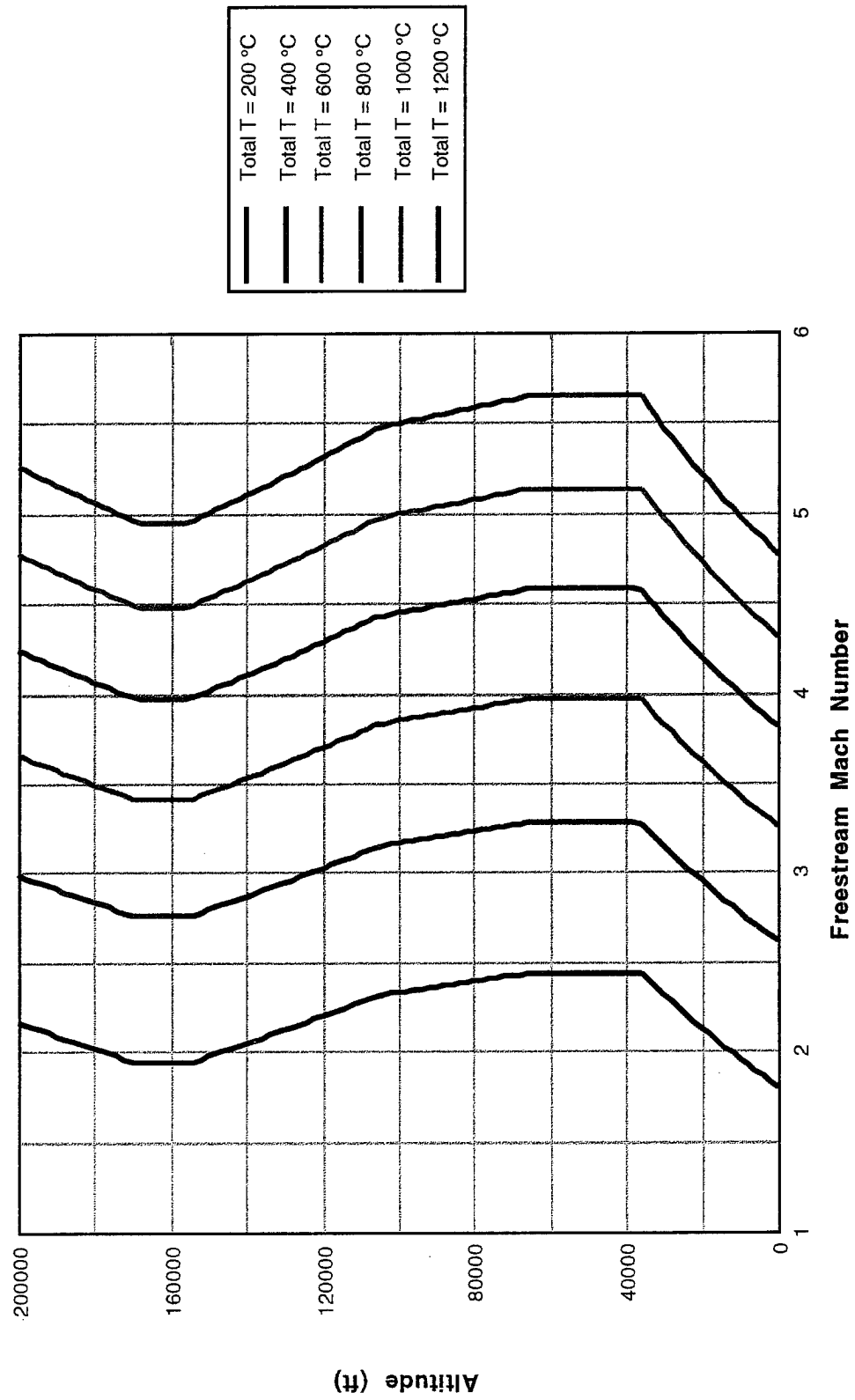


FIGURE 2. Free-Stream Mach vs. Altitude for Various Flow Total Temperatures (1976 U.S. Standard Atmosphere).

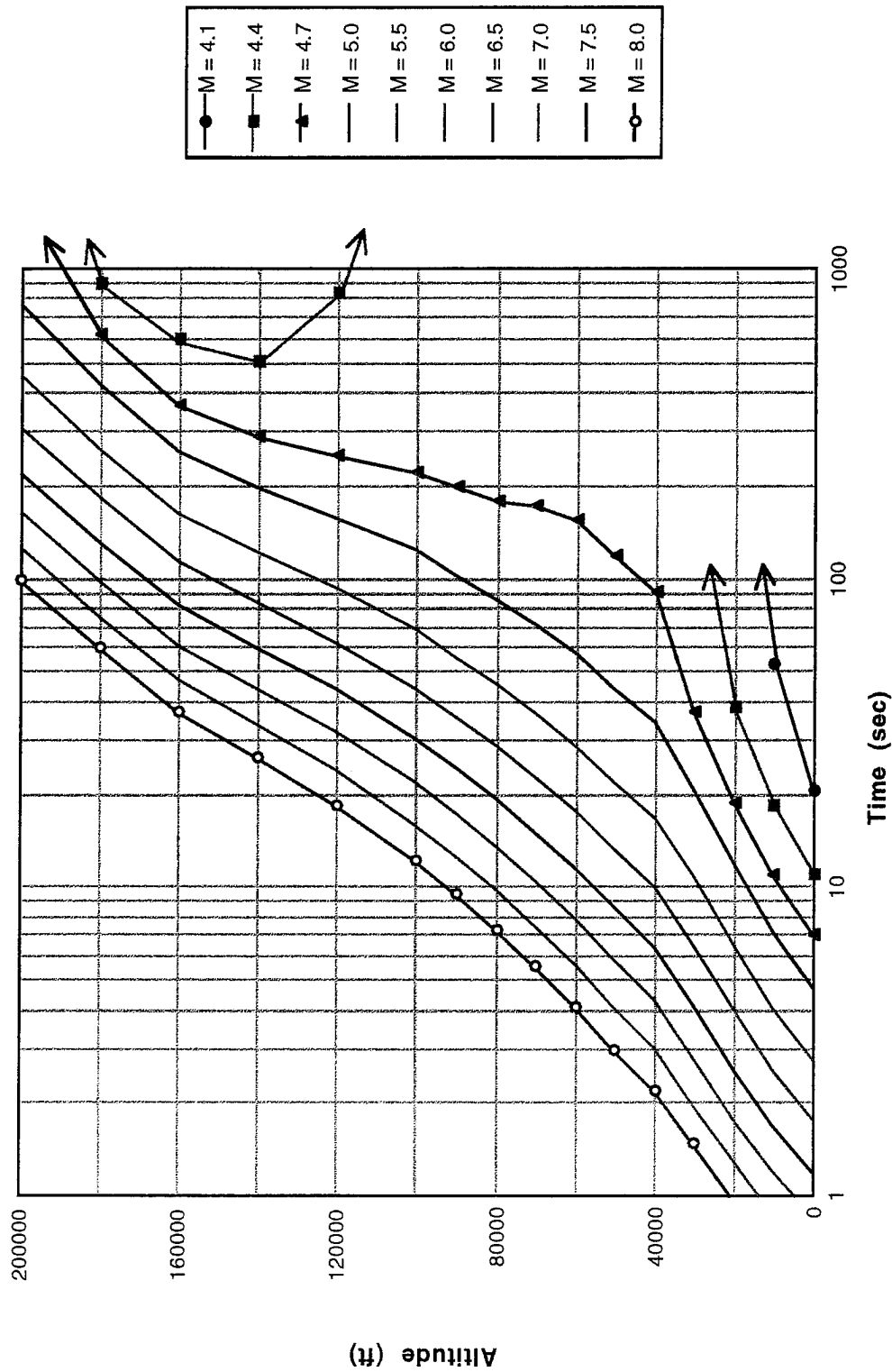


FIGURE 3. Time Required for a Diamond Dome to Reach 800°C in Standard Atmosphere for Various Free-Stream Mach Numbers (3.81-cm radius hemispherical dome, 2.54-mm thick, 27°C initially). Arrows point to data points off-scale.

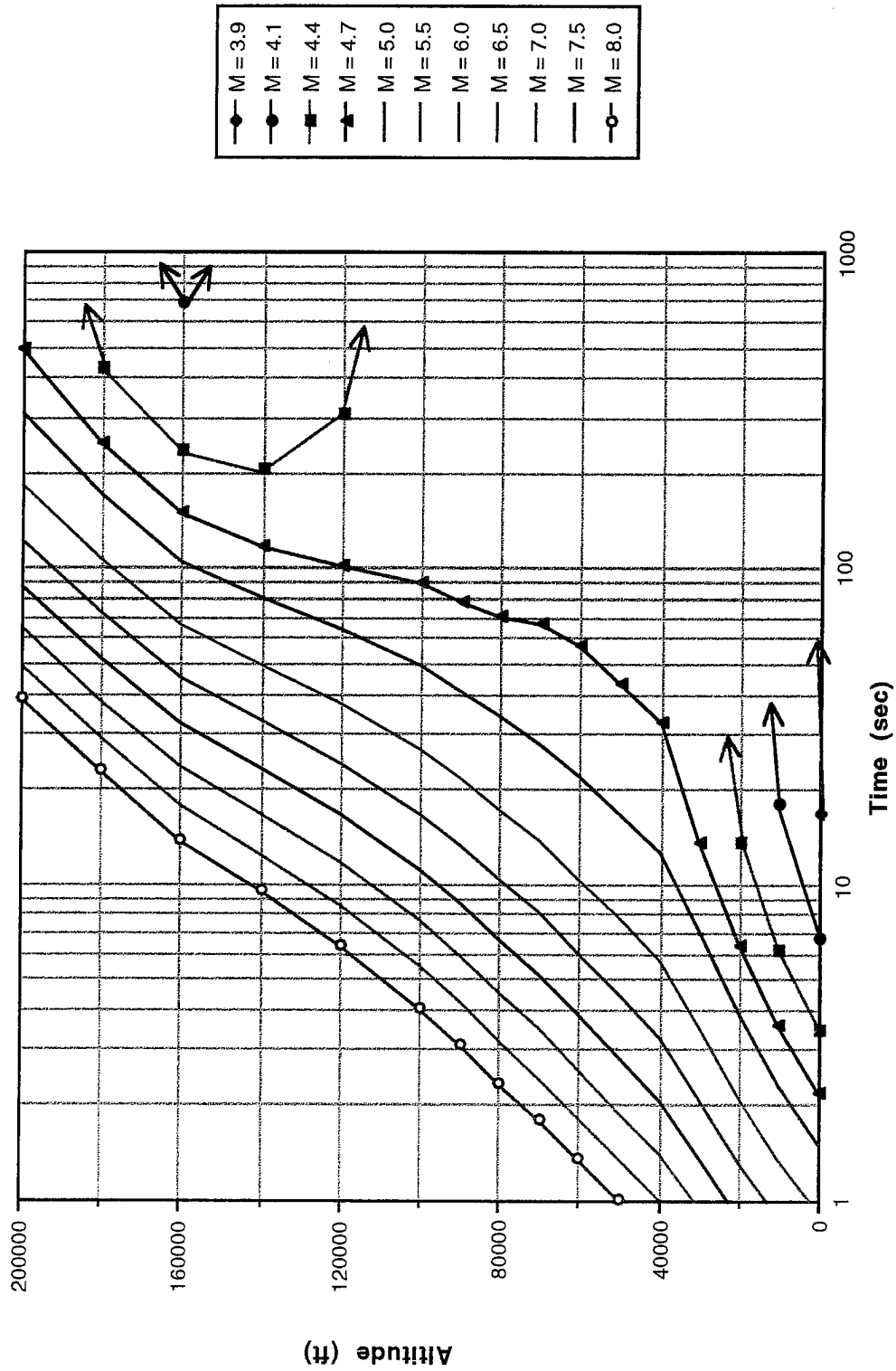


FIGURE 4. Time Required for a Diamond Dome to Reach 800°C in Standard Atmosphere for Various Free-Stream Mach Numbers (1-mm thick, 27°C initially).

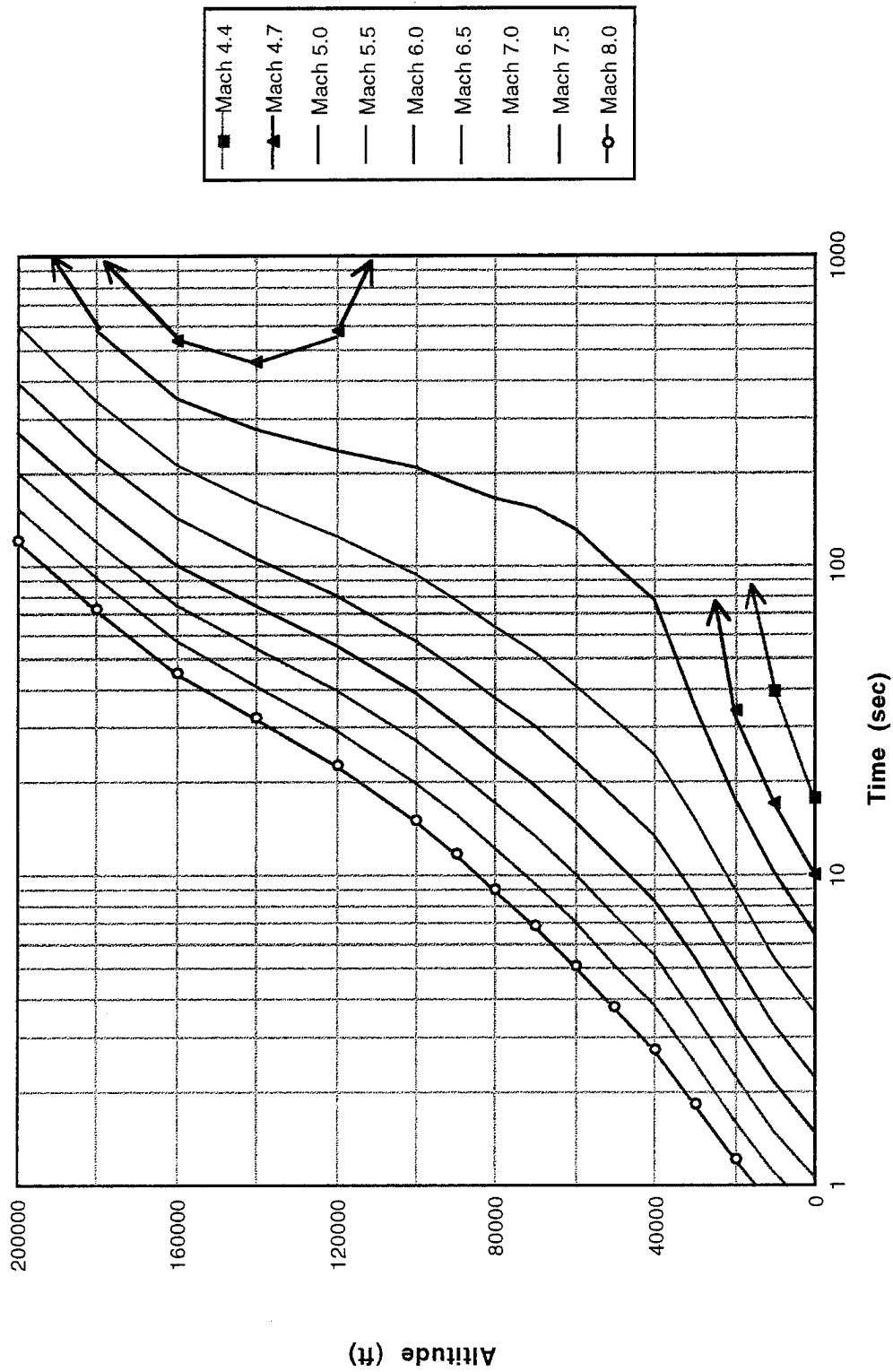


FIGURE 5. Time Required for a Diamond Dome to Reach 900°C in Standard Atmosphere for Various Free-Stream Mach Numbers (2.54-mm thick, 27°C initially).

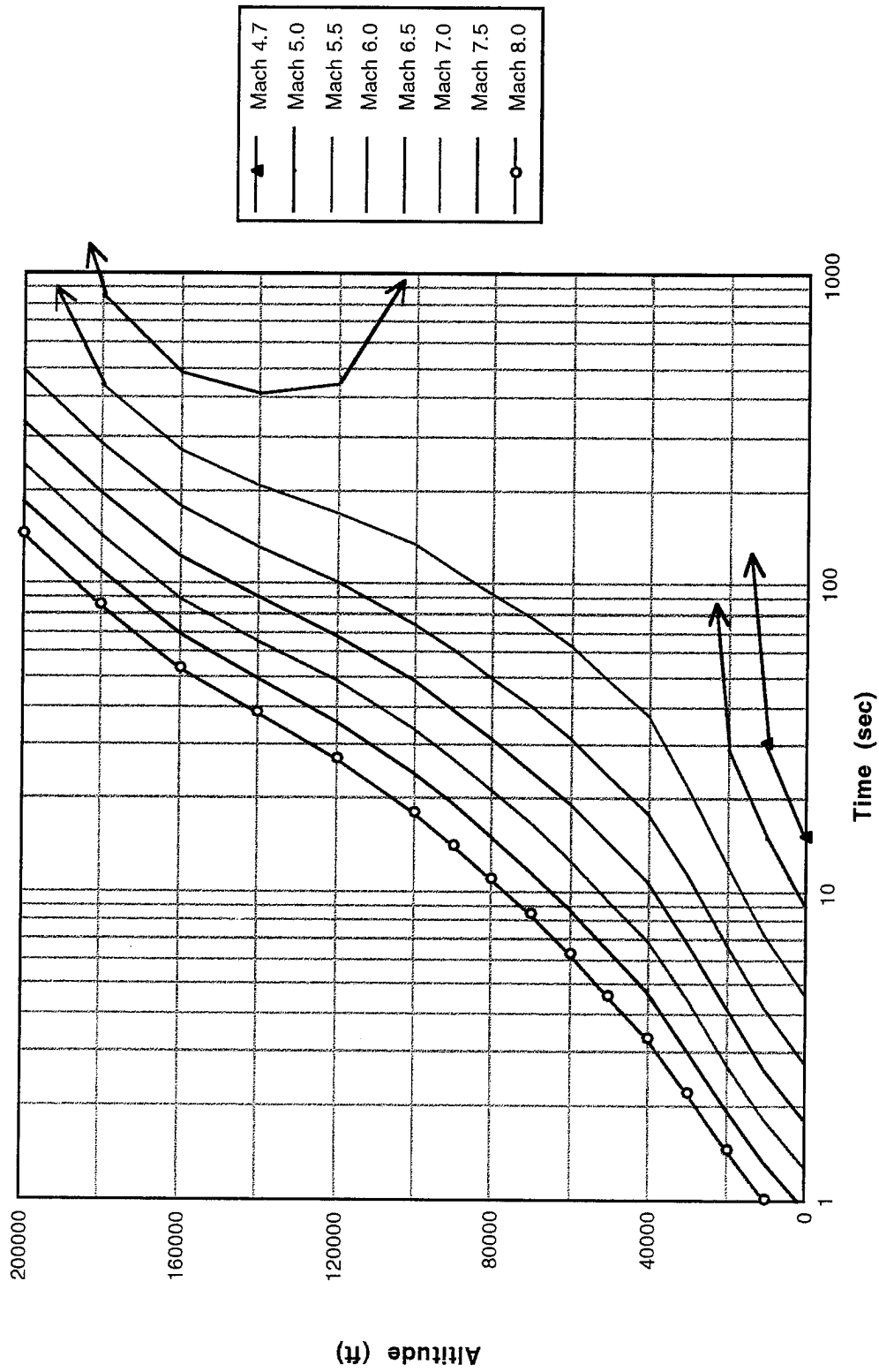


FIGURE 6. Time Required for a Diamond Dome to Reach 1000°C in Standard Atmosphere for Various Free-Stream Mach Numbers (2.54-mm thick, 27°C initially).

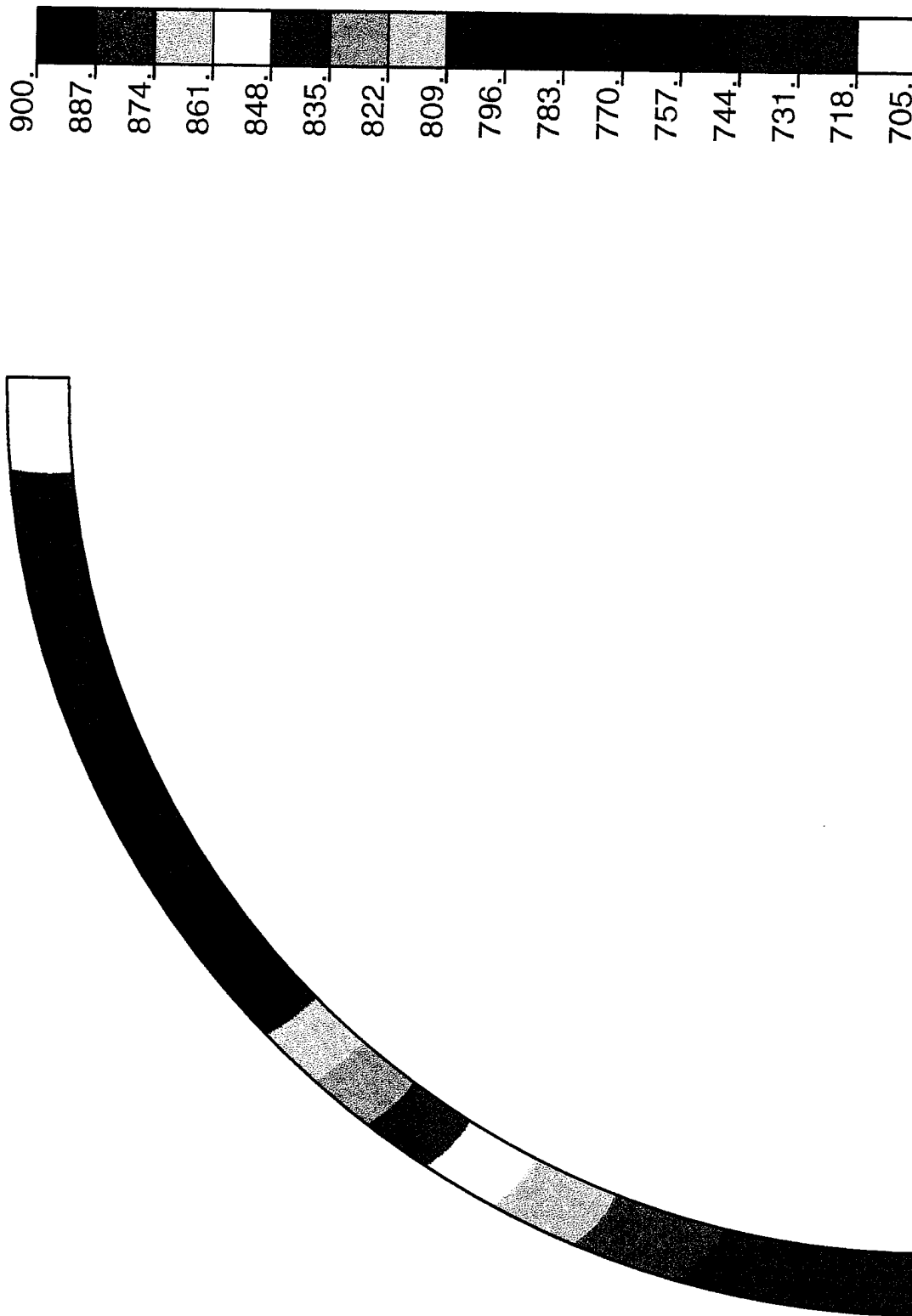


FIGURE 7. Temperature Contours in Degrees Centigrade for 2.54-mm-Thick Diamond Dome at Mach 5.5 and 20,000 ft When 900°C was Reached (8.96 s).

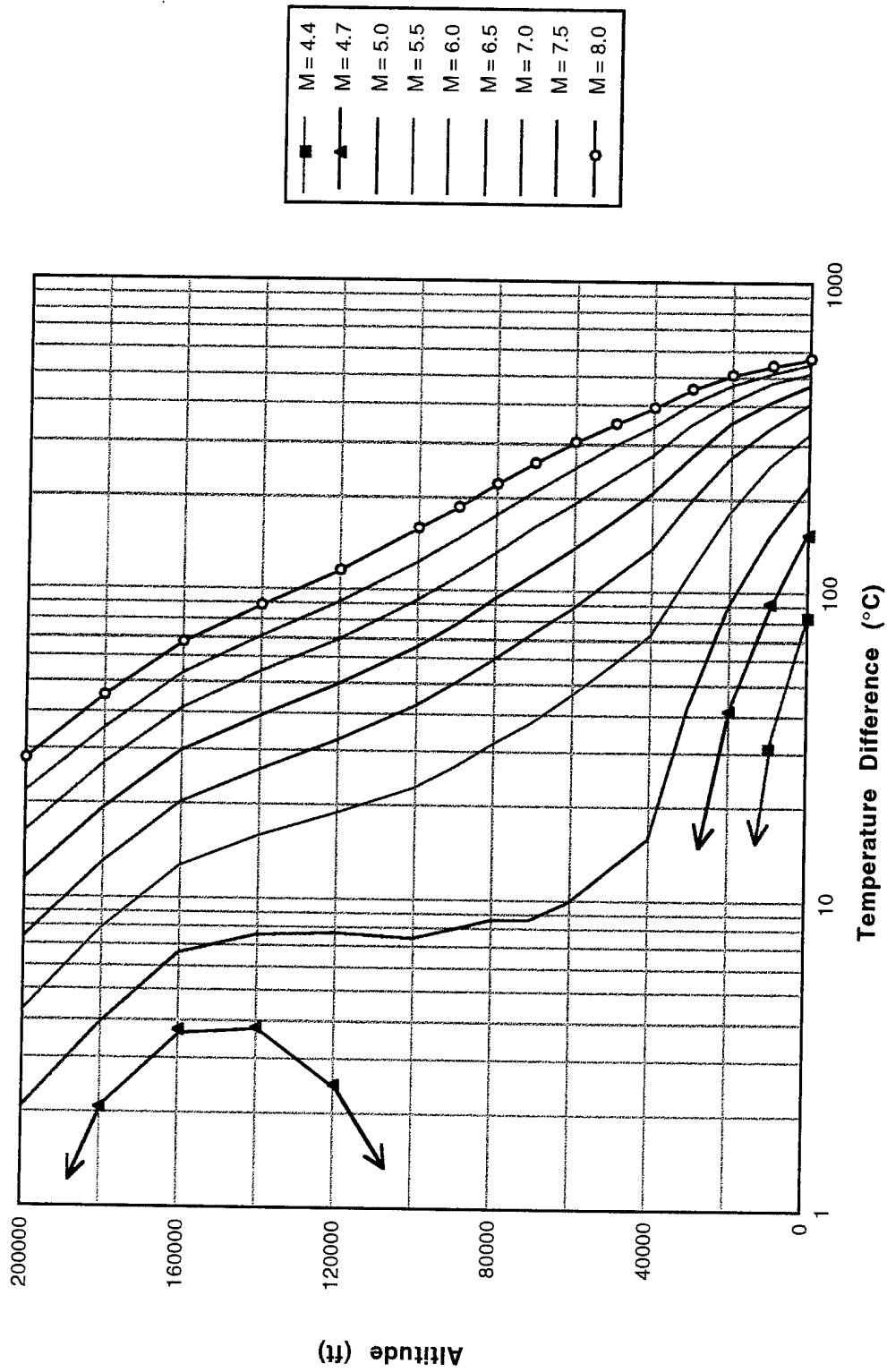


FIGURE 8. Maximum Temperature Variation on Surface of Diamond Dome When 900°C was Reached (2.54-mm thick, 27°C initially).

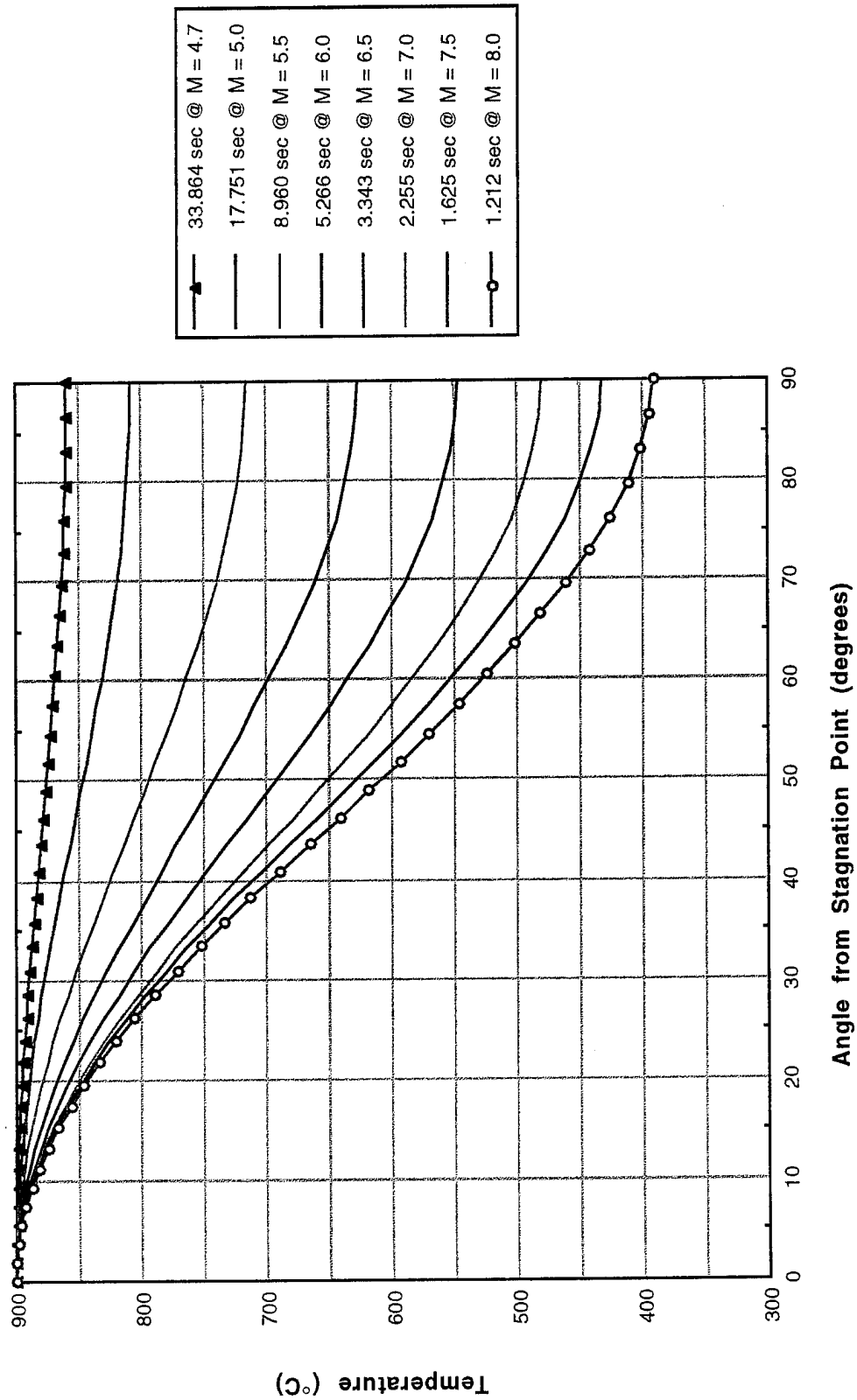


FIGURE 9. Diamond Dome Surface Temperatures at 20,000 ft (2.54-mm thick, 27°C initially).

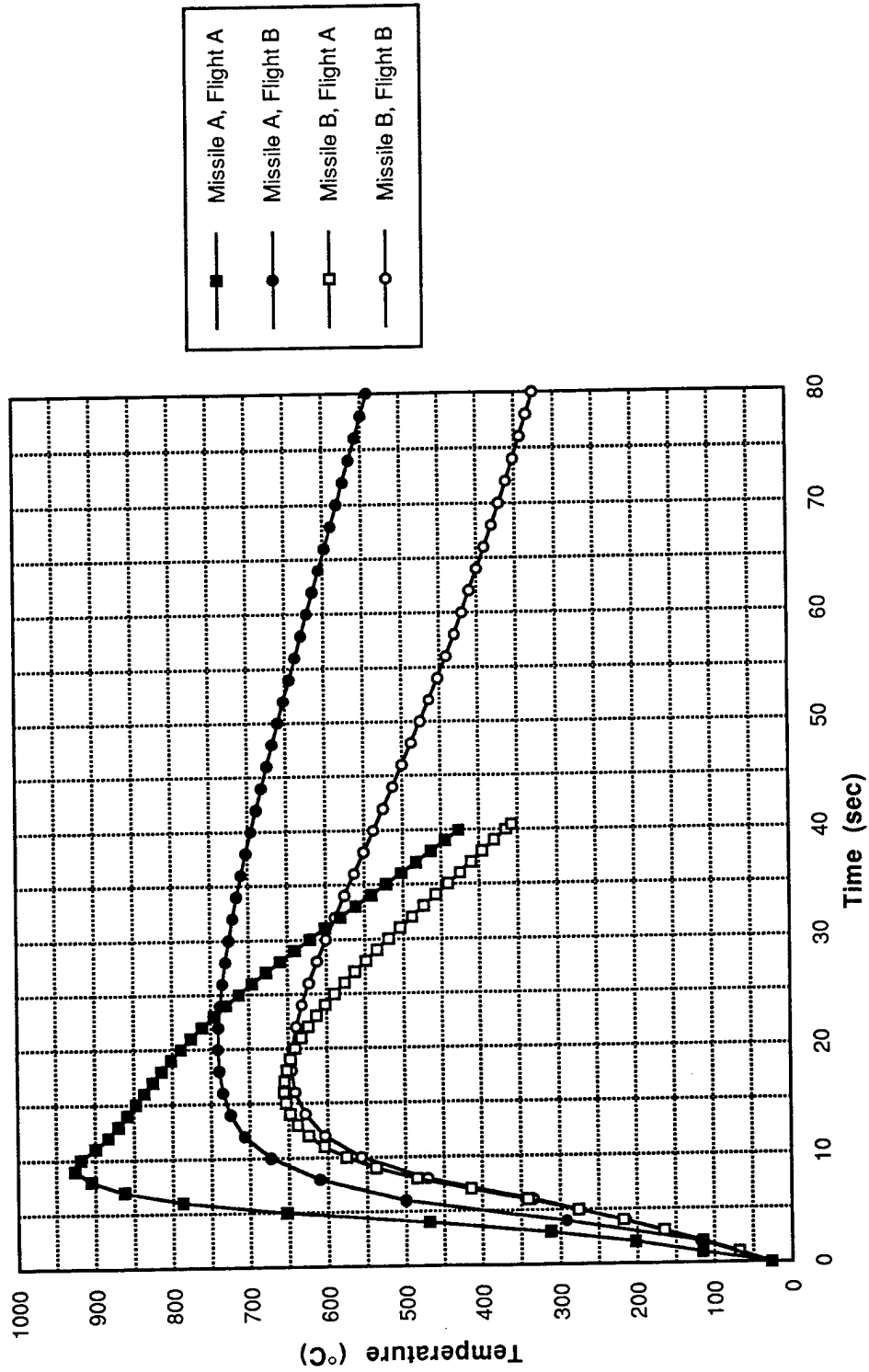


FIGURE 10. Diamond Dome Stagnation Point Temperature for Medium Range Missile Flight Profiles (1.5-mm thick, 27°C initially).

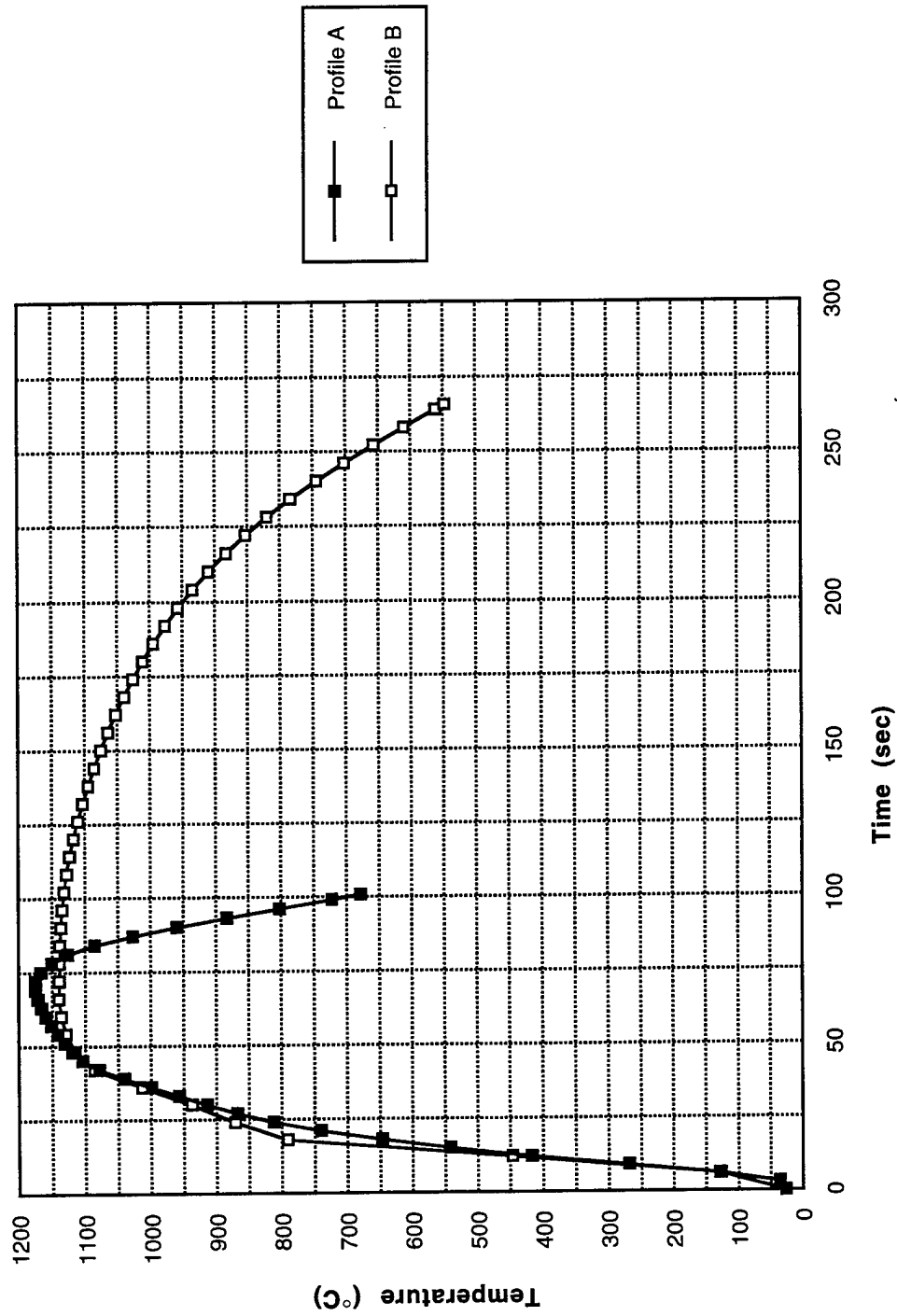


FIGURE 11. Diamond Dome Stagnation Point Temperature for Long Range Missile Flight Profiles (1.5-mm Thick, 27°C Initially).

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